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Baryon and strangeness enhancement at SPS, RHIC and LHC energies in the String Fusion Model

N. S. Amelin^a, N. Armesto^b, C. Pajares^c and D. Sousa^c

^a *Department of Physics, University of Jyväskylä, FIN-40351 Jyväskylä, Finland*

^b *Departamento de Física, Módulo C2, Planta Baja, Campus de Rabanales, Universidad de Córdoba, E-14071 Córdoba, Spain*

^c *Departamento de Física de Partículas Elementales, Universidade de Santiago de Compostela, E-15706 Santiago de Compostela, Spain*

Abstract

Strangeness and baryon enhancement in heavy ion collisions are discussed in the framework of the String Fusion Model. The Monte Carlo version of this model is shown to reasonably reproduce three of the features that have been pointed out as evidences of the finding of the Quark Gluon Plasma. Namely hyperon/antihyperon enhancement, dependence of the slope of the p_T distributions on the mass of the produced particles and on the centrality of the collision, are described. Predictions for RHIC and LHC energies are presented.

I. INTRODUCTION AND MODEL DESCRIPTION

In the last year a large excitement has arisen in the heavy ion physics community, related to the possibility of Quark Gluon Plasma (QGP) already been obtained at SPS energies [1]. In particular several signals were mentioned, which point out to the existence of QGP. Putting aside the abnormal J/ψ suppression and the excess of dileptons found, there are three signals related to baryon and strangeness production, namely the large enhancement of the (anti)hyperon yields (Λ , Ξ , Ω) in Pb-Pb collisions compared to p-Pb, observed by the WA97 [2] and the NA49 [3] Collaborations*; the linear increase of the inverse exponential slope of the p_T distributions ('temperature') in Pb-Pb collisions with the mass of the observed particle, except for Ω (for pions there is also a small departure from the straight line) [3,5]; and the different behaviour of the temperature between p-p and A-A collisions. Concerning this last feature, while the temperature in p-p collisions remains flat as a function of particle mass, in heavy ion collisions it increases as the mass increases. Furthermore, for a given mass, the heavier the colliding system, the higher the temperature [6]. These last two characteristics have been interpreted as the existence of an intrinsic freeze-out temperature and a collective hydrodynamical flow which is gradually developed: firstly, for S-S collisions, and, in a more clear way, in Pb-Pb collisions.

We would like to study these three signals, together with other important related data as ϕ production [7,8], different particle ratios [9] and stopping power [10], in a Monte Carlo code based on the String Fusion Model (SFM) [11,12]. Compared to previous versions, the model has been improved, including minijet production and rescattering of the produced secondaries in a standard way (an extensive description of these new features will be presented elsewhere [13]). Summarizing, hard collisions have been included using PYTHIA [14], in order to reproduce the non-exponential tail of the p_T spectrum experimentally measured in \bar{p} -p collisions at Sp \bar{p} S and TeVatron; this is crucial for the applicability of the model at RHIC and LHC. Rescattering is introduced as $2 \rightleftharpoons 2$ collisions [15] between mesons and baryons, taking into account both strangeness conserving and strangeness exchange reactions, and the possibility of the inverse processes as required by detailed balance. Only three cross sections are used: the first one for reactions involving Ω and $\bar{\Omega}$, the second one for reactions related to \bar{p} annihilation, and the third one for all other reactions.

In the String Fusion Model it is assumed that strings fuse when their transverse positions come within a certain interaction area. In the code we consider only fusion of two strings but there is a probability of fusion of more than two. An effective way of taking this into account is to increase the cross section for the fusion of two strings, for which we will take $\sigma_{fus} = 7.5$ mb. This value is crucial to reproduce the strangeness enhancement in central S-S and S-Ag collisions at SPS [12]. The fusion can take place only when the rapidity intervals of the strings overlap. It is formally described by allowing partons to interact several times, the number of interactions being the same both for projectile and target. The quantum numbers of the fused strings are determined by the interacting partons and their energy-

*A recent reanalysis [4] of Ξ data done by the NA49 Collaboration gives yields at midrapidity which are in much closer agreement to the WA97 [2] results than the previous analysis of NA49 [3].

momentum is the sum of the energy-momenta of the ancestor strings. The colour charges of the fusing string ends sum into the colour charge of the resulting string ends according to the SU(3) composition laws. The breaking of each fused string is due to the production of two (anti)quark complexes with the same colour charges Q and \bar{Q} as those at the ends of the string [11]. The probability rate is given by the Schwinger formula [16]

$$W \sim K_{\{N\}}^2 \exp(-\pi M_t^2 / K_{\{N\}}), \quad (1)$$

where $K_{\{N\}}$ is the string tension for the $\{N\}$ SU(3) representation, proportional to the corresponding quadratic Casimir operator $C_{\{N\}}^2$ [17]. In our case $C_{\{3\}}^2 = 4/3$, $C_{\{6\}}^2 = 10/3$ and $C_{\{8\}}^2 = 3$. Therefore, the $\{8\}$ and $\{6\}$ fused strings have a higher string tension, giving rise to larger heavy flavour and baryon/antibaryon production. Hard strings are not fused, their area being proportional to $1/p_T^2$. Some effect of the fusion of such strings could appear at LHC energies where, for instance, in central Pb-Pb collisions they amount for 35 % of the binary nucleon-nucleon collisions [13].

In principle, the fusion of strings means nothing related to a phase transition. On the contrary, percolation of strings [18] is a non-thermal second order phase transition. In this case, the key parameter is $\eta = \pi r^2 N / A$, which is the density of strings $N / \pi R_A^2$ (number of strings N produced in the overlapping area of the collision, $A = \pi R_A^2$ for central collisions) times the transverse size of one string πr^2 . The critical point for percolation is $\eta_c \simeq 1.12 \div 1.5$ depending on the profile function of the colliding nuclei [19]. With $r \simeq 0.2$ fm, this critical value means $9 \div 12$ strings/fm². The value of 9 is reached in central Pb-Pb collisions at SPS, in central Ag-Ag collisions at RHIC and in central S-S collisions at LHC. We expect for η around or greater than η_c , that the approximation of fusion of just two strings fails.

II. RESULTS AND CONCLUSIONS

In Fig. 1 we show our results for Ω , Ξ and Λ yields for p-Pb, and central Pb-Pb collisions at SPS with four different centralities, together with the experimental data. In order to disentangle the different processes contributing, in Fig. 2 it is shown the results of the code for central ($b \leq 3.2$ fm) Pb-Pb collisions without string fusion and rescattering, with string fusion, and with string fusion and rescattering. A reasonable agreement with data is obtained. Only the Ω 's are a little below the data (40 %). Similar results have been obtained in the Relativistic Quantum Molecular Dynamics model [20,21] by a mechanism of colour ropes which consider fusion of strings; also in the Ultra Relativistic Quantum Molecular Dynamics model [22,23] and in the HIJING model [24] by using an ad hoc multiplicative factor in the string tension. Also the Dual Parton Model [25], considering the possibility of creation of diquark-antidiquark pairs in the nucleon sea, together with the inclusion of diagrams which take into account baryon junction migration [25–27], can reproduce the experimental data (for Ω 's some rescattering has still to be added). The string fusion is the main ingredient to obtain a good agreement with $\bar{\Lambda}$ experimental data and also to reproduce the Ξ data. However the rescattering is fundamental to get enough Ω 's. Notice also that there is not any jumping between S-S and Pb-Pb. The most pronounced enhancement takes place between p-Pb and S-S. About $\bar{\Lambda}$, our results are higher than the WA97 data, its production being mainly determined by string fusion and hardly affected by rescattering.

This fact makes that our results for Pb-Pb are really an extrapolation in the model from the value for $\bar{\Lambda}$ production in central S-S collisions by the NA35 Collaboration, which was used to fix the fusion cross section σ_{fus} [12]. So, from the point of view of our model, there exists either a large $\bar{\Lambda}$ annihilation or a conflict between NA35 data for S-S and WA97 data for Pb-Pb.

In Fig. 3 we plot the inverse exponential slopes of the p_T distributions for different particles, together with the WA97 experimental data. A reasonable agreement is obtained. In particular it can be seen that the Ω slope is below the straight line both in the model and in data. Also our predictions for RHIC are presented. We see that the Ω is now on the straight line, so the decrease at SPS energies is due to energy-momentum conservation.

About ϕ enhancement, our results without fusion, with fusion, and with fusion and rescattering are 3.55, 4.20 and 5.35 respectively, in satisfactory agreement with experimental data, 7.6 ± 1.1 [8]. In Fig. 4 the stopping power is shown, i.e. the $p - \bar{p}$ rapidity distributions for central Pb-Pb collisions at SPS, compared with the experimental data [10], together with the predictions for RHIC and LHC energies. This quantity is essentially determined by the string fusion mechanism and rescattering only plays a minor role. As discussed for strangeness enhancement, it has been pointed out that baryon junction migration [25–27] will enhance the stopping power due to diagrams additional to the usual ones of the Dual Parton Model. The inclusion of these diagrams also explains the SPS data. We have not taken into account such diagrams to avoid double counting, because in the fusion of strings they are partially included in an effective way. In Fig. 5 the antiproton rapidity distribution in central Pb-Pb collisions is presented and compared to the experimental data [28]; a great suppression of the antiproton yield is seen, due to rescattering.

In Table I our results for the ratios between different particles are compared with the experimental data [9] for Pb-Pb central collisions at SPS. We include our predictions for RHIC and LHC in Table II. Some comments are in order: First, we observe an overall, rough agreement with the SPS data. Second, our results are not very different to those of statistical models [30,31]. However, the saturation of the strangeness enhancement in our case has nothing to do with thermal and/or chemical equilibrium. In string fusion the enhancement of the different strange particle yields is similar to a threshold behaviour: First there is a pronounced rise and afterwards, a saturation. The main difference in the predictions for RHIC and LHC between the String Fusion Model and statistical models is the overall charged multiplicity, which is respectively 950 and 3100 for SFM and 1500 and 7600 for statistical models [32] (assuming initial temperatures of 500 and 1000 MeV for RHIC and LHC respectively).

Let us emphasize that we obtain a reasonable agreement with the experimental data in three of the features advocated as signals of QGP production. We are only below data in the Ω production by less than a factor 2. It is possible to improve this agreement arranging the corresponding rescattering cross sections. However, we think that the usefulness of any Monte Carlo is in the overall picture and not in obtaining detailed fits which require a fine tuning. For this reason we do not change our rescattering cross sections.

Nevertheless, related to the Ω production, it is tempting to speculate about percolation of strings as a possible explanation of the discrepancy. It is just around Pb-Pb central collisions at SPS energies where the critical point η_c , which corresponds to $9 \div 12$ strings/fm², is placed. Close to this point, the formation of at least one cluster of strings through the whole reaction

area is possible. Therefore it is expected that the String Fusion Model does not work there. This point can be checked at RHIC. There, the density of strings formed in central Ag-Ag collisions is also around 9 and therefore the number of Ω 's would be above the string fusion prediction.

As a last point, we compare our results with the preliminary data of the PHOBOS Collaboration at RHIC [33]. For charged particles we obtain $dN/d\eta|_{|\eta|<1} = 520$ and 585 for the 6 % more central Au-Au collisions at $\sqrt{s} = 56$ and 130 GeV per nucleon respectively, to be compared with 408 ± 12 (stat) ± 30 (syst) and 555 ± 12 (stat) ± 35 (syst). Our prediction for $\sqrt{s} = 200$ GeV per nucleon with the same centrality criterium is $dN/d\eta|_{|\eta|<1} = 635$.

In conclusion, the agreement of the model with baryon and strangeness experimental data at SPS is satisfactory, so the SFM code can be useful as a tool for simulations of the forthcoming experiments at RHIC and LHC energies.

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TABLES

	NF	F	$F + R$	$Exp.$
Λ/Λ	0.036	0.256	0.202	0.128 ± 0.012
Ξ^+/Ξ^-	0.959	0.414	0.342	0.266 ± 0.028
Ω^+/Ω^-	1.0	0.543	0.454	0.46 ± 0.15
Ξ^-/Λ	$2.58 \cdot 10^{-3}$	0.042	0.067	0.093 ± 0.007
Ξ^+/Λ	0.069	0.069	0.113	$0.195 \pm .023$
Ω/Ξ	0.0606	0.046	0.106	$0.195 \pm .028$

TABLE I. SFM results for different particle ratios in central Pb-Pb collisions at SPS, compared with experimental data ($Exp.$) [9]. Results are presented without fusion (NF), with fusion (F) and with fusion and rescattering (F+R).

	$RHIC(F)$	$RHIC(F + R)$	QCM	$Rafelski$	$B - M$	$LHC(F)$
Λ/Λ	0.638	0.600	0.84	0.49 ± 0.15	0.906	0.889
Ξ^+/Ξ^-	0.860	0.823	0.84		1.	0.965
Ω^+/Ω^-	1.207	0.975	1.	1.	1.	1.047
Ξ^-/Λ	0.071	0.108			0.125	0.084
Ξ^+/Λ	0.096	0.149		0.18 ± 0.2	0.138	0.091
Ω/Ξ	0.078	0.208				0.055
Λ/\bar{p}	0.386	0.726	0.87	2.4 ± 0.3		0.355
$\bar{p} p$	0.499	0.380	0.67		0.097	0.829

TABLE II. SFM results for different particle ratios in central Pb-Pb collisions at RHIC and LHC, following the same convention as in Table I. For comparison, results from other models (Quark Coalescence Model (QCM) [21], Rafelski [21] and $B - M$ [21,29]) for RHIC are included.

FIGURES

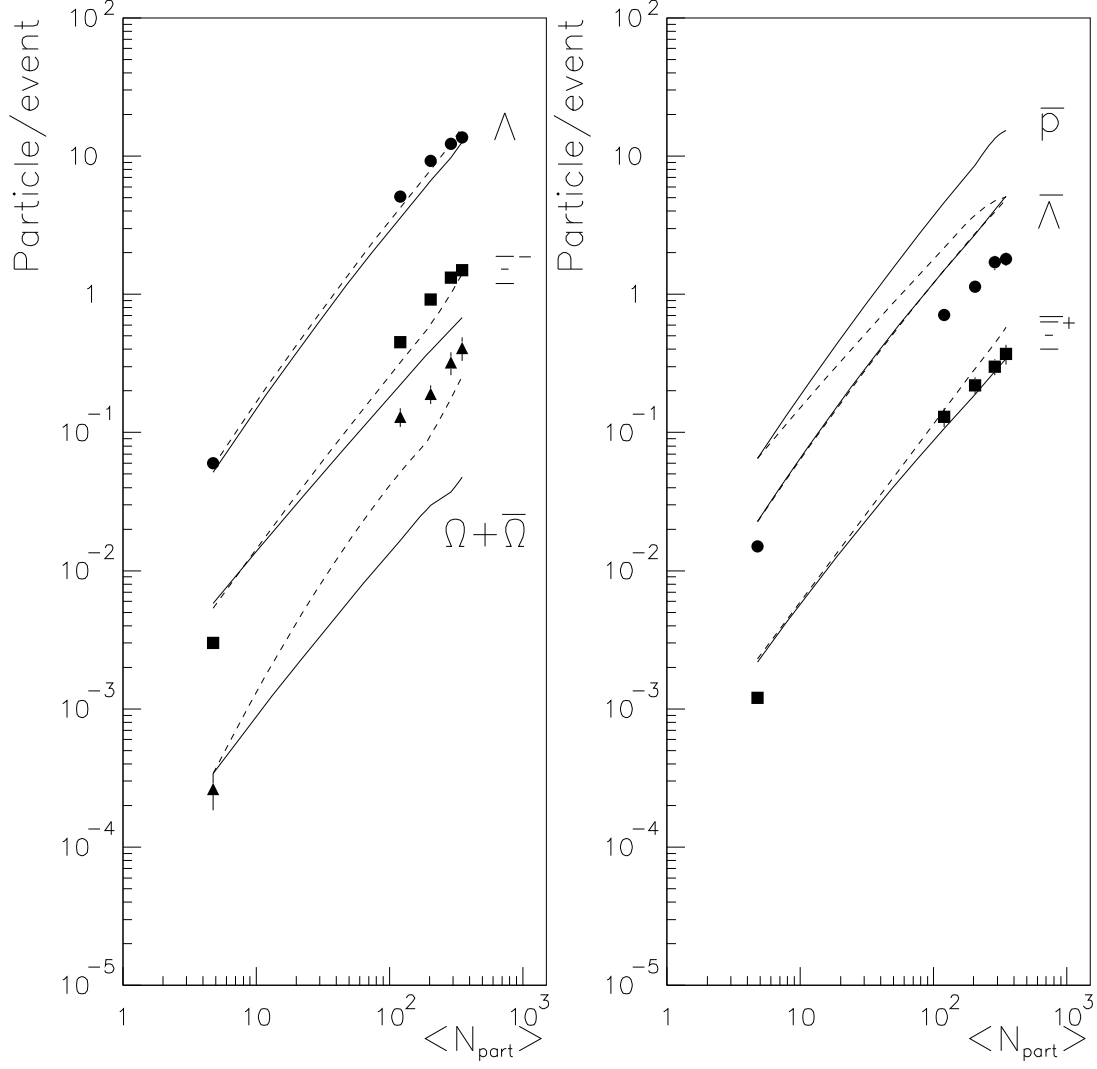


FIG. 1. Yields per unity of rapidity at central rapidity as a function of the number of wounded nucleons for Λ , Ξ^- and $\Omega + \bar{\Omega}$ (left) and for \bar{p} , $\bar{\Lambda}$ and $\bar{\Xi}^+$ (right) for p-Pb collisions and four different centralities in Pb-Pb collisions at SPS energies. Full lines represent our calculation with string fusion and dashed lines with fusion and rescattering. Experimental data are from the WA97 Collaboration [2].

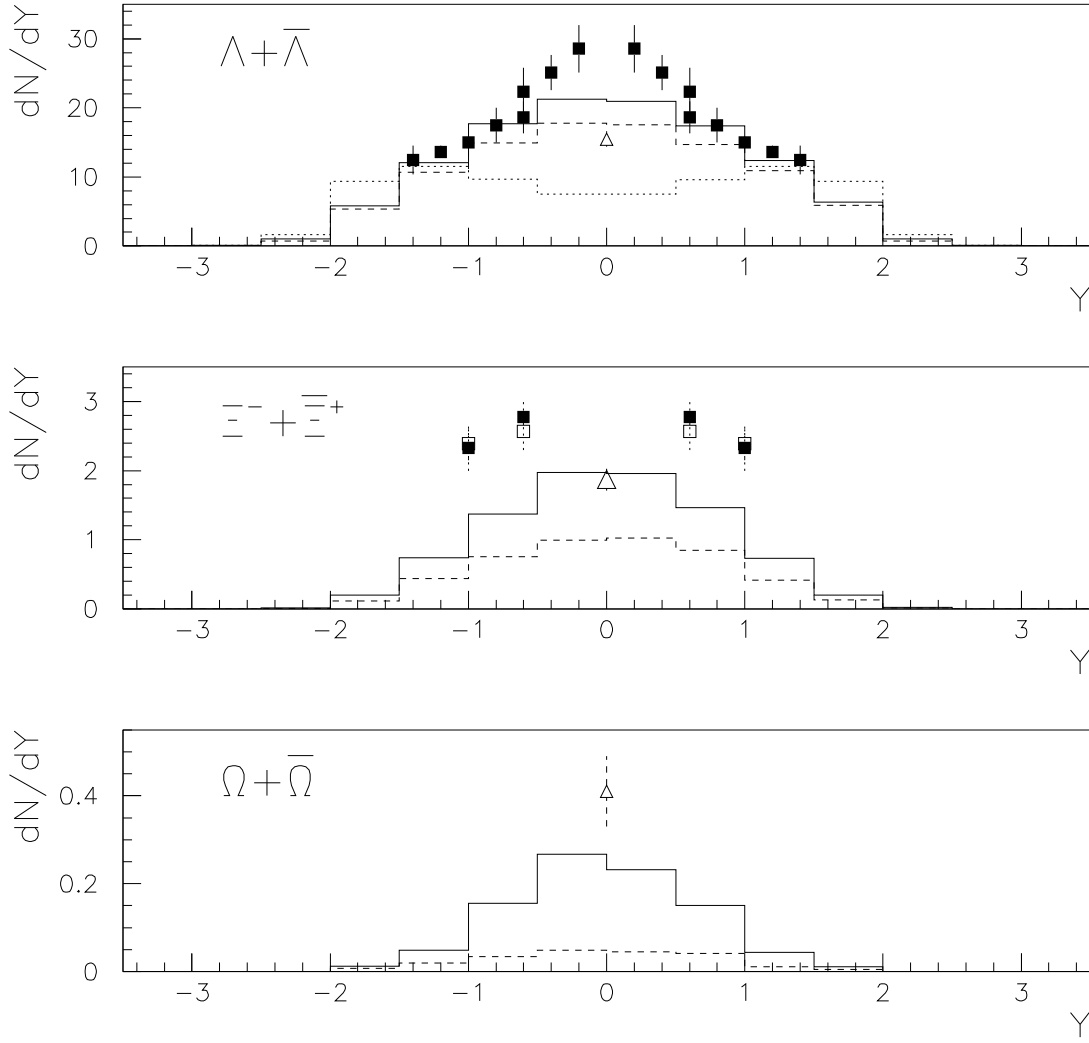


FIG. 2. SFM results (dotted line: without fusion, dashed line: with fusion, solid line: with fusion and rescattering) for strange baryon production in central Pb-Pb collisions (5 % centrality) at SPS compared with experimental data from the WA97 Collaboration [2] (triangles) and the NA49 Collaboration [3] (squares).

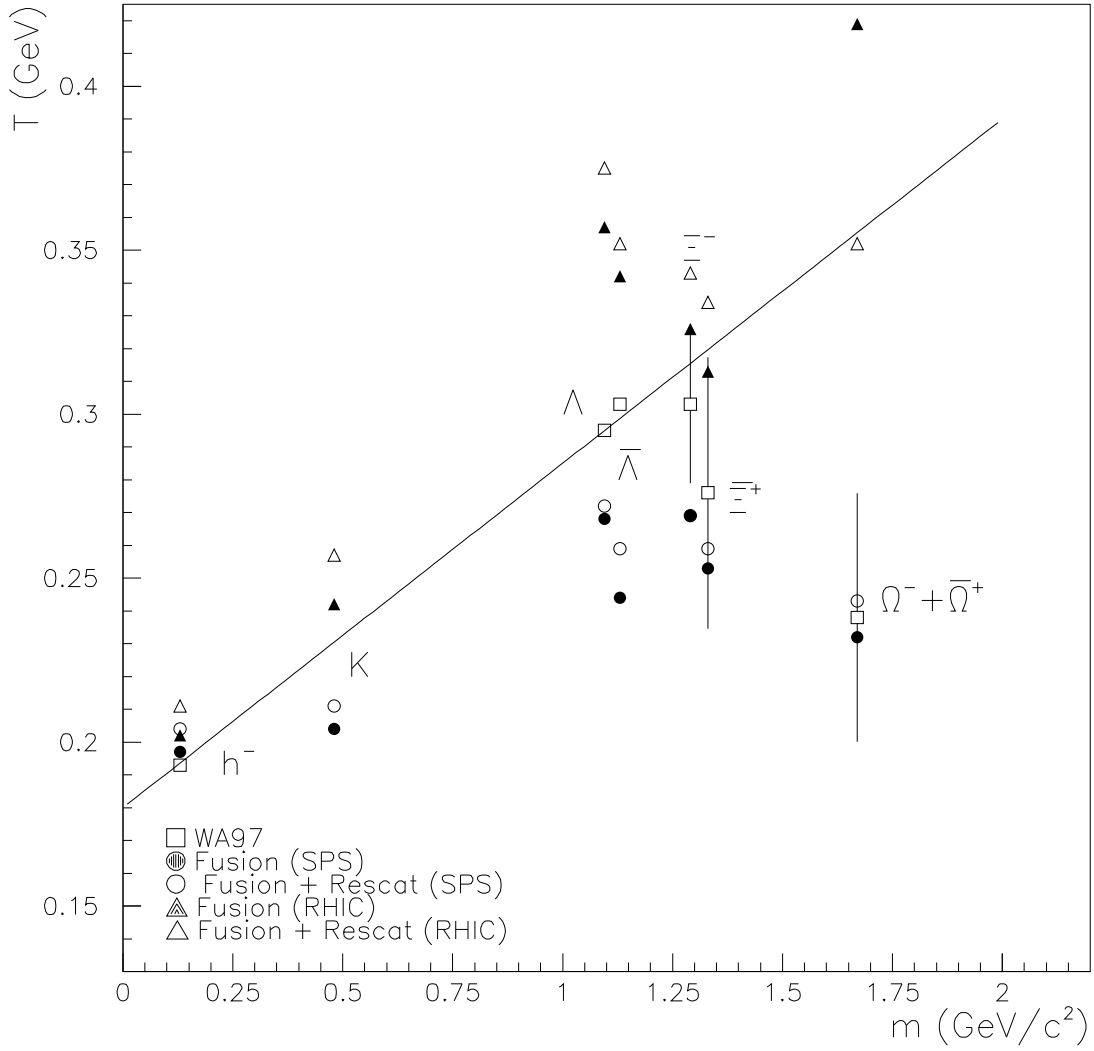


FIG. 3. SFM results (filled circles: with fusion, open circles: with fusion and rescattering) for the inverse exponential slope of the p_T distributions of different particles versus the transverse mass of the particles in central (5 % centrality) Pb-Pb collisions at SPS, compared with the experimental data of the WA97 Collaboration [5] (open squares). We also present our predictions for RHIC energy with fusion, filled triangles, and with fusion and rescattering, open triangles.

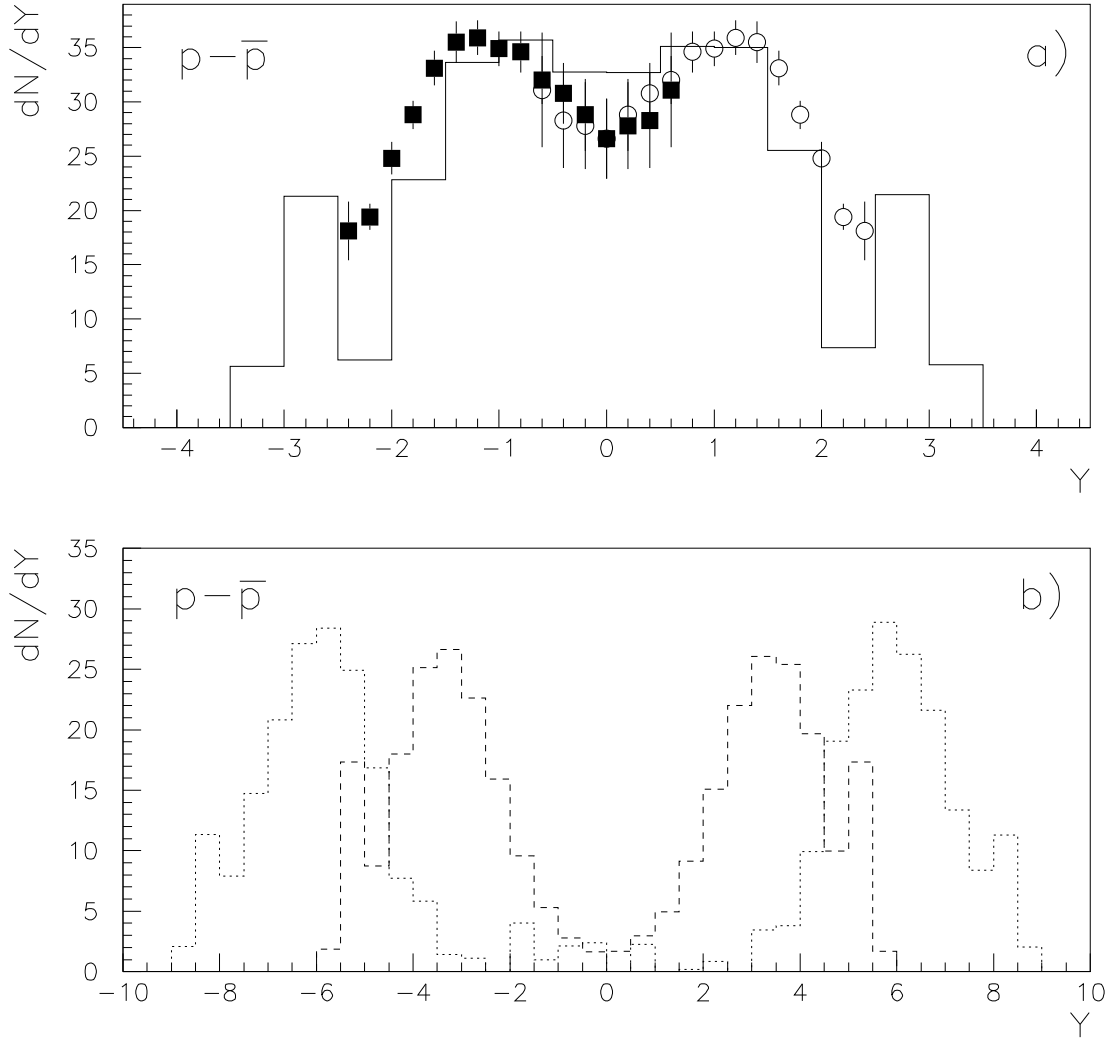


FIG. 4. SFM results for the $p-\bar{p}$ rapidity distribution in central (5 % centrality) Pb-Pb collisions at SPS (solid line), RHIC (dashed line) and LHC (dotted line), compared with experimental data at SPS [10].

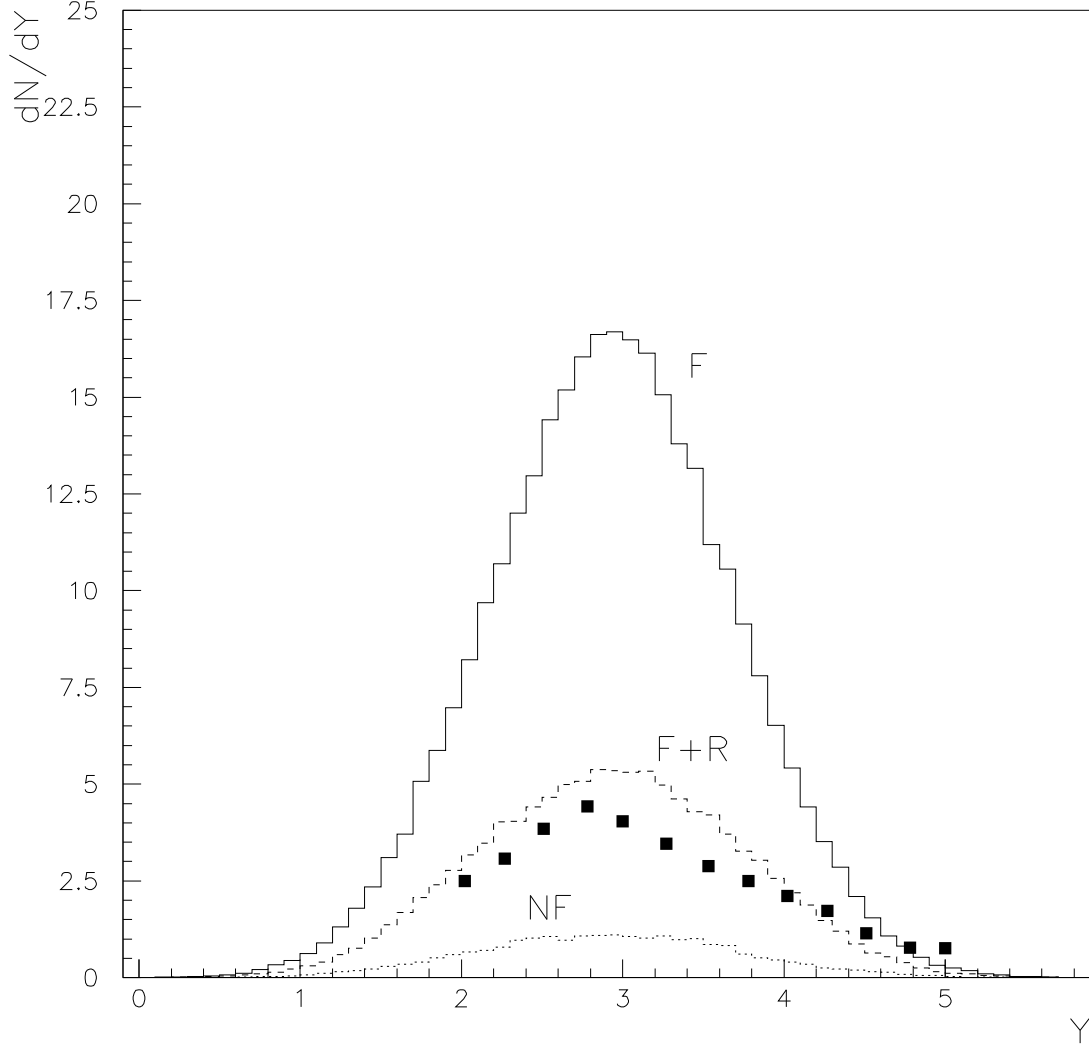


FIG. 5. SFM results (dotted line: without fusion, solid line: with fusion, dashed line: with fusion and rescattering) for the \bar{p} rapidity distribution in central (5 % centrality) Pb-Pb collisions at SPS, compared with experimental data [28].